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FINAL REPORT

A STUDY OF BEAM COUPLERS FOR INTEGRATED OPTICS

February 1, 1973 - January 31, 1977

for

Office of Naval Research
Department of the Navy

under

Contract Nos: N00014-67-A-04-38-0014
N00014-75-C-0421

Submitted by

T. Tamir, Professor
Principal Investigator

Report No. POLY EE/EP 77-031

DEPARTMENT OF ELECTRICAL ENGINEERING AND ELECTROPHYSICS

POLYTECHNIC INSTITUTE OF NEW YORK

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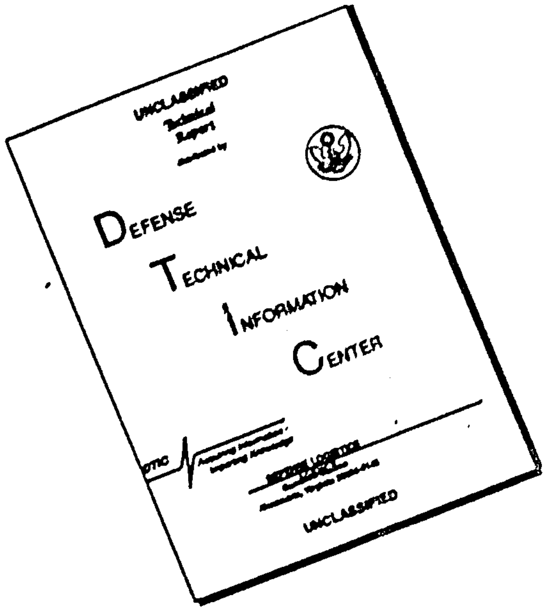

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The
~~Our~~ theoretical study of beam couplers that convert an optical beam into a guided surface wave, or vice-versa, has produced the following results: (1) A unified leaky-wave approach to beam couplers of the prism and grating varieties; (2) A procedure for beam shaping by varying the parameters of the guiding surface-wave structure; (3) A rigorous solution of scattering by dielectric gratings, which form the basis of grating couplers; (4) A demonstration of a novel directional blazing effect of

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surface waves by asymmetric gratings; (5) An approximate analysis of the properties of dielectric gratings, which has an accuracy that is adequate for their practical design; (6) The development of equivalent electric network for describing the coupling operation of dielectric gratings, and (7) The formulation of simple criteria for the design and fabrication of such gratings.

I. SCOPE AND SUMMARY OF RESULTS

The work initially proposed was a theoretical study of devices that couple a light beam into a thin-film optical waveguide or, conversely, they couple a guided surface wave out of the waveguide by radiating energy in the form of an emerging beam. While other investigations have also been concerned with beam couplers, the intent of the proposed study was to examine the capabilities of such couplers for beam shaping purposes.

Our investigation has therefore addressed itself first to the beam-shaping properties of beam couplers. The results have shown that couplers of the grating variety are best suited for achieving a large variety of beam-shaping functions. However, as dielectric gratings pose a formidable boundary-value problem if their performance needs to be accurately predicted, a considerable portion of our efforts was devoted to developing analytic techniques for treating such problems. By using both rigorous and approximate methods, we have derived simplified procedures that facilitate the design of grating couplers having high efficiencies, special characteristics and other desirable performance features.

The principal achievements of our study can be summarized by the following: (references are those given in Sec. IV.A, p.6-7)

A. We completed the development of an approach [1,5,10] that enables one to view the beam-coupling operation in terms of a single leaky wave supported by the thin-film structure. This view is applicable to all beam couplers and thus provides a unified approach.

B. Beam-shaping functions of couplers were shown [5] to be realized by imposing a slow variation on the leaky-wave properties of the guiding structure.

C. A rigorous solution of scattering problems by dielectric gratings was obtained [2,3,7]. By providing highly accurate numerical results, this solution serves as a powerful tool in testing simpler but less accurate perturbation solutions.

D. Directional blazing of gratings was first demonstrated by our study [4,6]. By using this blazing effect in conjunction with a beam-shaping procedure, grating couplers could be designed with nearly 100% efficiency.

E. A simple perturbation approach to the analysis of grating couplers was developed, which was shown [8,9] to yield sufficiently accurate results for design purposes.

F. An interpretation of the operation of dielectric gratings was formulated [12,13] in terms of equivalent electric networks. These networks facilitate the physical understanding of complex scattering problems involving the coupling process.

G. By combining the results under A through F above, simple criteria were derived [14] for the systematic design of grating couplers.

II. OUTLINE OF INVESTIGATIONS PERFORMED

The results described in the foregoing section were often achieved by studies that were performed in parallel. The studies outlined below do not follow chronological order. Instead, the work is described by breaking it down into several convenient topics.

A. Variable coupling and beam shaping.

While the use of prism couplers with variable air gaps for beam shaping purposes was also recognized by others, the application of tapered dielectric gratings in that context was first suggested by us [T. Tamir and H.L. Bertoni, "Unified Theory of Optical Beam Couplers," Digest of Tech.Papers, Topical Meeting of Integrated Optics, Guided Waves, Materials and Devices; Opt. Soc., Am., N.Y., pp. MB3/1-MB3/4, 1972]. Our suggestions were based on a unified approach to couplers of both the prism and grating varieties. This approach viewed the coupling devices in terms of leaky-wave structures whose operation is determined by the leakage parameter α, which describes the local radiation of power away from the structure [1,10].

It was then soon recognized by us that grating couplers are more versatile in producing beam-shaping functions than prism couplers. This is due to the fact that gratings are periodic structures and therefore they can support leaky waves that are traveling in either a forward or a backward direction with respect to the power flux in the optical guide. In contrast, prism couplers can only support forward waves.

We therefore studied the performance of tapered couplers and emphasized the effects of gratings with parameters that vary along their longitudinal direction. In particular, we have shown [5] that properly designed couplers can produce not only perfect coupling (i.e., 100% efficient couplers), but they can also achieve specific beam shaping, such as beam splitting.

B. Analysis of Dielectric Gratings

The study of beam shaping by grating structures with variable parameters has shown the feasibility of their use in beam shaping. On the other hand, this study has also revealed the serious lack of analytic tools in dealing even with grating structures in which the longitudinal variation is absent.

We have therefore spent a considerable portion of our effort in reviewing the available methods for dealing with electromagnetic scattering by dielectric gratings, and in developing new approaches and specific solutions. In particular, we have derived an exact solution to the problem of wave scattering and guiding by gratings with rectangular profiles [2,3]. This solution can be extended to other profiles by subdividing the grating into a suitable number of thin sections, each of which is then approximated by a rectangular profile. Such an extension was also derived [7] and applied to two-layered grating structures [4,6] for deriving interesting blazing effects, which are discussed in Section C.2 below.

Unfortunately, the calculation of numerical results via the exact solution requires a computer program that is quite complex and too time consuming. In particular, the amount of time needed for calculations may become excessively long for TM modes and/or for grating profiles requiring a large number of subsections. The exact solution is therefore primarily intended for establishing the accuracy of other simpler solutions, which are only approximate. In this context, however, the exact solution serves as a very powerful tool for determining the accuracy of those simpler but approximate solutions.

The simpler solutions that had been in existence at the time we looked into these questions were almost exclusively based on perturbation approaches which assumed thin grating layers. We therefore successfully developed [8,9,14] a modified perturbation approach which, by comparing it with our rigorous solution [7], was found to yield accurate results for gratings of arbitrary thickness. Our approach was found so satisfactory that it has subsequently been used by others in the context of both grating couplers and other optical devices. [See, for example, the contents and bibliography in: W.Streifer et al., "On Grating Coupled Radiation for Waveguides," IEEE J.Quant Electron., vol. QE-12, pp. 717-732, Nov. 1976.]

A particularly attractive aspect of the perturbation approach developed by us is that it provides a description of the grating in terms of an equivalent tansmission-line network. Such a network enables one to gain a good physical insight into the grating operation. In particular, we have shown [12,13] that simple considerations in the context of the equivalent network can provide straightforward explanations to complex scattering phenomena.

C. Practical Applications of Analytical Results

While the mathematical tools described under Section II.B above were being developed, they have also been continuously applied to situations of practical interest. Some of the more interesting results are listed here:

1. Effect of grating shapes

Most of the results obtained in the literature refer to grating profiles having rectangular corrugations. Our analysis has revealed [6,14] that even moderage changes from the rectangular shape have a relatively small effect on the scattering properties of gratings. However, profiles that are quite different from rectangular shapes can produce significant effects, as discussed further below. Thus, while fabrication tolerances in the grating profiles are generally not critical, particular grating shapes can be chosen for special effects.

2. Directional blazing

A particularly interesting and useful application achieved by properly shaping the grating profile is directional blazing. This happens when the grating scatters the guided optical wave selectively into the air region (above the grating) or into the substrate region (below the grating). Such behavior is essential in realizing a grating coupler that achieves maximum efficiency by producing a single outgoing beam (into one of the two exterior regions) rather than by radiating energy into two separate beams (one each in the air and substrate regions). The feasibility of the [illegible]ectional blazing effect was first predicted by us analytically [4] [illegible]e have thereafter also formulated basic design considerations [1[illegible] [illegible]or achieving this effect. The experimental verification of this [illegible]ing effect has been reported later by others.

3. Effect of imperfections

We have studied [11] the effects on beam coupling due to the presence of imperfections on the finished grating. While local imperfections appear to have negligible adverse effects, gradual changes in the grating profile can be very harmful to the overall coupling efficiency. Thus, a small taper which extends over a large portion of the grating can drastically reduce the coupling efficiency because of phase mismatch over the grating surface.

4. Simple design criteria

By combining the perturbation approach to the grating problem [8,9] with a network analysis of particular situations [12,13], we have derived simple, explicit algebraic formulae for the leakage parameter of the grating, as well as for the coupling efficiency [14]. These formulae would be easy to utilize in designing grating couplers having prescribed characteristics, with applications to both laboratory and industrial uses.

The above contains only the more important results of our analysis. Other aspects, such as the effect of dielectric losses on coupling performance, the roles of grating height, periodicity width and other parameters on wave scattering, as well as many other related topics, have also been examined [1-14].

III. CONTRIBUTING PERSONNEL

The individuals who contributed to the investigation described here are the following:

Dr. T. Tamir, Professor, Principal Investigator
Dr. H.L. Bertoni, Professor
Dr. S.T. Peng, Research Associate Professor
Dr. A. Saad)
Mr. K. Handa) Graduate
Mr. J.T. Lin) Students
Mr. K. C. Chang)

Because of the limited budget of the contract and the wide scope of the investigation, Professors Bertoni and Peng, and Mr. Handa were supported by other research funding; also, Professor Tamir and Dr. Saad had additional support. The sources for the additional funds have been the National Science Foundation and the Joint Services Electronics Program. However, Mr. Lin and Mr. Chang have been supported only by the ONR contract.

The investigation has also included a small cooperative effort with Dr. Fradin and Dr. Cheo of United Technologies Research Center, Hartford, Connecticut. The results of this effort have been discussed in Section II.C3 and they have been presented at a professional meeting [11].

IV. PUBLICATIONS AND OTHER ACTIVITIES

The principal results of our investigations have been published in articles and presented at professional meetings, as listed below.

A. Journal Articles

The numbers of the following articles are used as references throughout this report.

1. T. Tamir, "Inhomogeneous Wave Types at Planar Interfaces: III-Leaky Waves," Optik, vol. 38, pp 269-297; August 1973.

2. S.T. Peng, H.L. Bertoni and T. Tamir, "Analysis of Periodic Thin-Film Structures with Rectangular Profiles," Optics Comm., vol. 10, pp. 91-94; January 1974.

3. S.T. Peng, T. Tamir and H.L. Bertoni, "Analysis of Thick-Grating Beam Couplers," Digest of Technical Papers, Topical Meeting on Integrated Optics, Optical Soc. of Am., pp. TuB8-1 to TuB8-4; 1974.

4. S.T. Peng and T. Tamir, "Directional Blazing of Waves Guided by Asymmetric Dielectric Gratings," Optics Comm., vol. 11, pp. 405-409; August 1974.

5. A. Saad, H.L. Bertoni and T. Tamir, "Beam Scattering by Non-uniform Leaky-Wave Structures," Proc. IEEE, vol. 62 (Special Issue on Rays and Beams), pp. 1552-1561; November 1974.

6. S.T. Peng, and T. Tamir, "Effect of Groove Profile on the Performance of Dielectric Grating Couplers," Proc. Symp. Optical and Acoustical Micro-Electronics, Polytechnic Press, Brooklyn, N.Y., pp. 377-392, 1975.

7. S.T. Peng, T. Tamir and H.L. Bertoni, "Theory of Periodic Dielectric Waveguides," IEEE Trans. Microwave Theory and Techniques (Special Issue on Integrated Optics and Optical Waveguides), vol. MTT-23, pp.123-133; January 1975.

8. K. Handa, S.T. Peng and T. Tamir, "Improved Perturbation Analysis of Dielectric Gratings," Appl. Phys., vol. 5, pp. 325-328; January 1975.

9. S.T. Peng and T. Tamir, "TM-Mode Perturbation Analysis of Dielectric Gratings," Appl. Phys., vol. 6, pp. 35-38; May 1975.

10. T. Tamir, "Leaky Waves in Planar Optical Waveguides," Nouv. Rev. Opt. vol. 6, pp. 273-284; Sept.-Oct. 1975 (INVITED PAPER).

11. D.W. Fradin, P.K. Cheo, S.T. Peng and T. Tamir, "Effects of Imperfections on the Efficiency of Optical Couplers," Tech. Digest, Topical Meeting on Integrated Optics, Salt Lake City, Utah, pp. WD-1 - WD-4; January 1976.

12. T. Tamir and S.T. Peng, "Network Methods for Dielectric-Grating Applications," Digest of Tech. Papers, 1976 Int. Microwave Symp., Cherry Hill, N.J., pp. 27-29; June 1976.

13. T. Tamir and S.T. Peng, "Network Methods for Integrated Optics Devices," Proc. Intern. Conf. Applic. Holography and Data Processing, Pergamon Press, Oxford, 1977.

14. T. Tamir and S.T. Peng, "Analysis and Design of Grating Couplers," Appl. Physics (to be published).

B. Meeting Papers

Most of the articles above have been preceded by technical papers presented at professional meetings, as listed below.

(a) S.T. Peng, T. Tamir and H.L. Bertoni, "Leaky-Wave Analysis of Periodic Couplers," 1973 Spring OSA Meeting, Denver, Colorado; March 1973.

(b) S.T. Peng, T. Tamir and H.L. Bertoni, "Analysis of Thick-Grating Beam Couplers," Topical Meeting on Integrated Optics, New Orleans, La.; January 1974.

(c) S.T. Peng and T. Tamir, "Effects of Groove Profile on the Performance of Dielectric Grating Couplers," MRI Symp. Optical and Acoustical Micro-Electronics, New York, N.Y.; April 1974. (INVITED PAPER).

(d) A. Saad, H.L. Bertoni, and T. Tamir, "Beam Scattering by Non-Uniform Leaky-Wave Structures," 1974 Fall URSI Meeting, Boulder, Colo.; October 1974.

(e) S.T. Peng and T. Tamir, "Analysis of Dielectric Waveguides," 1974 Fall URSI Meeting, Boulder, Colo.; October 1974.

(f) T. Tamir and S.T. Peng, "Blazing Effects in Dielectric Gratings," 1974 Fall OSA Meeting, Houston, Texas; October 1974.

(g) T. Tamir, "Leaky-Wave Field Configurations in Optical Waveguides," Colloquium on the Optics of Guided Waves, Paris, France; April 1975. (INVITED PAPER).

(h) T. Tamir, S.T. Peng and H.L. Bertoni, "Beam and Waveguide Couplers," International Electro-Optics Conference and Laser Exposition, Anaheim, Calif.; November 1975. (INVITED REVIEW PAPER).

(i) D.W. Fradin, P.K. Cheo, S.T. Peng and T. Tamir, "Effects of Imperfections on the Efficiency of Optical Couplers," Topical Meeting on Integrated Optics, Salt Lake City, Utah; January 1976.

(j) T. Tamir and S.T. Peng, "Network Methods for Dielectric-Grating Applications," 1976 Int. Microwave Symp., Cherry Hill, N.J.; June 1976.

(k) T. Tamir and S.T. Peng, "Network Methods for Integrated Optics Devices," Intern. Conf. Applic. Holography and Optical Data Processing, Jerusalem, Israel; August 1976.

(l) T. Tamir, S.T. Peng and K.C. Chang, "Leaky-Wave Characteristics of Dielectric Gratings with Arbitrary Profiles," to be presented at the URSI Intern. Electromagnetics Symp, Stanford, Calif.,in June 1977.

C. Book

The experience gained from this research study enabled T. Tamir, Principal Investigator, to publish "Integrated Optics" (Springer-Verlag , 1975) as editor and contributor of two chapters ("Introduction" and "Beam and Waveguide Couplers"). The book also includes contibutions by E. Garmire, J.M. Hammer, H. Kogelnik and F. Zernike, each of whom wrote one chapter dealing with his or her specialty in the area of integrated optics.

This book has received excellent reviews and, although two years in print by now, it is still considered a state-of-the-art manual. A particularly noteworthy citation was given in the May 1976 issue of Physics Today, where each chapter of the book served as a separate reference in the review article entitled "Integrated Optics" by E.M. Conwell.

D. Doctoral Dissertations

The contract has provided partial support for the completion in 1974 of a Ph.D. (Electrophysics) thesis entitled "Scattering of Optical Beams from Slowly Varying Leaky Wave Structures," by Dr. A. Saad.

Another doctoral student, Mr. K.C. Chang, has been supported by this contract and is expected to complete his dissertation in 1978. His work deals primarily with blazed dielectric gratings.

E. Patent

The original ideas involving the design of blazed dielectric gratings, as discussed in Section II.C.2, served as patent disclosure, which was filed on July 9, 1975, through the Patent Advisor, Office of Naval Research, Boston, Mass. The patent was awarded to T. Tamir and S.T. Peng under the title "Directional Radiation by Asymmetrical Dielectric Gratings," No. 3982810.

V. REFERENCES:

As already noted before, all references are listed under Sec. IV.A.

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